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HIGH - FREQUENCY VOLTAGE MEASUREMENTS

BY M. C. SELBY

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Preface

This report on r-f measurements contains material written for inclusion in a Handbook of Physical Measurements to be published by the National Bureau of Standards.

The objectives are: (1) to present an up-to-date conspectus of fundamental techniques used in scientific research, laboratory and commercial measurements as well as their relative merits, (2) to cover all principles and methods that have met with any degree of success but not necessarily to compile all available material in encyclopedical form, (3) to meet the need of the professional worker and graduate student somewhat more comprehensively than the presently available handbooks do.

A considerable amount of the material presented is based on work done at this Bureau. Bibliography is omitted because the references given leading in turn to further references and bibliography are considered adequate.

Recognition and thanks are due to the authors listed in the references for their kind permission to quote some of these data and reproduce some drawings and curves, as well as to the N. B. S. editorial readers for valuable suggestions and cooperation.

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Introductory note

Standard procedures of r-f voltage measurements are at the present time based upon d-c calibrations with a standard cell as the primary reference. For maximum accuracy direct substitution is made of d-c for r-f sinusoidal voltage. Reliability is insured by cross-checking results with one or more independent calibration methods based on different principles. In the light of present-day experience at these frequencies, measurements to accuracies of approximately 1 percent may be considered of high precision. (This is to be differentiated from percentage accuracy of "full scale readings" usually given in individual instrument calibrations.) Assuming that d-c quantities can be obtained to 0.1 percent, all methods employing measurements directly in terms of d.c. without frequency corrections may be classified as primary-standard methods. Reproducibility of results, as well as agreement between individual primary-standard methods, is expected to be within ± 1 percent or better. Methods permitting a reproducibility and agreement with primary-standard techniques of the order of ± 5 percent will be referred to as "moderate precision" measurements. One must differentiate between the terms "Precision" and "accuracy." "Precision" refers to sensitivity, incidental variations and other errors of observation, while "accuracy" refers to the true value

of the quantity measured. A measurement may therefore be precise and not accurate, but not vice versa, i. e., once a measurement is accurate to a certain degree it must also be precise to the same degree.

The most suitable primary-standard r-f voltage measurement methods seem to be:

(a) Power measurement
(b) Current and resistance measurement
(c) Deflection of cathode-ray beam
(d) The electrostatic voltmeter

Methods not suitable for d-c calibration are:

(e) Vacuum tube voltmeters
(f) Rectifiers (nonthermionic)

1. Accurate high-precision methods based on d-c measurements.

(a) Power measurement.

In this method the reistance vs temperature characteristic of a bolometer is utilized for measuring conducted power and voltage.

A fundamental assumption of this method is that the r-f resistance of a particular bolometer is equal to its d-c resistance. The usual procedure is to substitute r-f power for a part of the d-c power fed into a bolometer bridge as shown in Fig. 1. Standard r-f voltage is then obtained across the bolometer. This method is applicable up to 300 Mc over an approximate range of 0.1 to several volts. Precautions must be observed in mounting the bolometer so that the voltmeter under calibration be connected directly across an r-f current-carrying circuit element having negligible series reactance.

Thermistors or Wollaston-wire type bolometers are generally used. A thermistor is a semiconductor such as uranium oxide ($U_3 O_8$), or a mixture of nickel oxide (NiO), having a large negative resistance-temperature coefficient [1,2]. A Wollaston wire is a platinum wire of the order of 0.001 mm in diameter drawn inside a silver wire; this silver coat is removed over a small section by etching with a solution of nitric acid (HNO_3); the exposed platinum core constitutes the active section of the bolometer. Typical thermistors have a resistance vs temperature sensitivity approximately 10 times larger than Wollaston wire, will carry considerably higher overloads, are superior in mechanical ruggedness, and have a larger thermal time constant [53].

Fig. 1 shows an elementary circuit diagram of a bridge employing two thermistors. The general expression for the r-f voltage is

$$E = \frac{1}{R_T + R_b} \left[R_T R_L (V_{R_2} - V_{R_1})(2 V_o - V_{R_2} - V_{R_1}) \right]^{1/2} \qquad (1)$$

where

E is the r.m.s. value of the voltage across the two thermistors in parallel,

V designates d-c voltages with the proper subscript. V_o, the voltage across the battery, is assumed constant with load variations.

Subscripts 1 and 2 designate respective values before and after the r-f voltage is applied.

$R_L = \frac{R_a R_c}{R_a + R_c}$, the load presented to the r-f source.

R_a and R_c are individual thermistor resistances.

$R_T = R_a + R_c$.

C, C' are d-c blocking condensers.

The following special cases are of practical significance:

(1) Matched bolometers ($R_a = R_c$), unequal-arm bridge ($R_b \neq R_T$), relatively low V_o, ($R_1 = 0$):

This seems to be the most convenient arrangement because it obviates the necessity of decoupling chokes (to keep r-f power out of the bridge). Greater accuracy is obtained by measuring V_{R_2} alone (as compared with measuring a small difference between two relatively large voltages), especially when E is low in magnitude.

$$E = \frac{R_T}{2(R_T + R_b)} \left[V_{R_2}(2V_o - V_{R_2}) \right]^{\frac{1}{2}} \qquad (2)$$

(2) Matched bolometers, unequal-arm bridge, relatively high V_o:

This is the case when it is advisable to maintain bridge-arm resistances of the same order of magnitude, thereby assuring bridge sensitivity sufficient for high precision. V_o is usually not continuously adjustable. $R_1 \neq 0$.

$$E = \frac{R_T}{2(R_T + R_b)} \left[(V_{R_2} - V_{R_1})(2V_o - V_{R_2} - V_{R_1}) \right]^{\frac{1}{2}} \qquad (3)$$

(3) Single bolometer ($R_c = 0$, $C' = 0$),

unequal-arm bridge, $R_1 = 0$.

This arrangement eliminates the necessity of matching bolometers and removes the possibility of only one of the two carrying the entire r-f load. This could occur, for example, when operation takes place over a negative resistance portion of thermistor characteristics.

$$E = \frac{R_T}{(R_T + R_b)} \left[V_{R_2}(2V_o - V_{R_2}) \right]^{\frac{1}{2}} \qquad (4)$$

(4) Single bolometer, equal-arm bridge:

$$E = 1/2 \left[(V_{R_2} - V_{R_1})(2V_o - V_{R_2} - V_{R_1})\right]^{1/2} \qquad (5)$$

The major advantage of having $R_b \neq R_T$ arises when a relatively small value of $(V_{R_2} - V_{R_1})$ as compared with V_{R_2} has to be measured as is the case at very low values of E. Other modifications may occasionally be desirable such as a single-bolometer unequal-arm bridge with high V_o, $(R_1 \neq 0)$, or an unmatched two-bolometer bridge when R_a and R_c are known individually and are expected to remain stable in either equal or unequal arm bridges.

To obtain maximum accuracy, precision potentiometers and a galvanometer of proper sensitivity are desirable. Among the precautionary requirements of this method, especially in measuring low-level voltages are the following: Constant ambient temperature, stable V_o (low-discharge batteries are preferred), stability of the resistances in the circuit, and accurate determination of their values, sinusoidal r-f voltage source.

(b) Current meter in series with resistance.

In employing this method to obtain accuracies of about 1%, the d-c calibration of the current indicating device and the value of the series resistor must be known to 0.5%. Both must remain constant at all frequencies under consideration. In addition the mechanical arrangement must be such that all the indicated current passes through the resistor. If the voltage drop across the current meter is also a part of the voltage measured, then the combined impedance of meter and resistance connected in series must remain essentially resistive. Thermoelements may be used in series with special resistors[3,4] up to a frequency of several megacycles to measure voltage levels from several millivolts to approximately 50 volts. Some of the difficulties encountered at higher frequencies are stray resistor capacitances and stray fields affecting the thermocouple circuit. Because the resistance of the thermocouple circuit is very much lower than the heater resistance, stray fields may upset the d-c calibration considerably[5].

This method may be modified by using the voltage drop across the heater (current-carrying element) as a standard. Under these conditions the impedance across its terminals must be essentially resistive and its value must be determined at each voltage level. Skin effect, inductance and power dissipation limit both the frequency and voltage ranges. Another limitation is the requirement of some independent means to indicate the current level; photoelectric calibration of the glow of the current-carrying conductor seems satisfactory. This method is applicable up to approximately 30 Mc[4].

(c) Cathode-ray beam deflection.

This method is based upon the well-known deflection of an electron beam by an electric field. One elementary circuit arrangement is shown in Fig. 2 where the essential elements of a high-vacuum cathode-ray tube are indicated.

The deflection is

$$D = E\ \max\ \frac{\ell y}{2V_a d} \tag{6}$$

Where V_a is the accelerating potential of the beam, ℓ is the effective length of the deflecting field, and y is the effective length of the beam between this field and screen.

The procedure in measuring E is to first adjust the zero spot position by setting V_1 with $V = 0$ and $E = 0$. The r-f voltage is then applied and the position of either end of the deflection trace on the screen is restored to the original position of the spot by applying the proper value of V; this value of V is then equal to E peak, provided the transit time and other frequency errors are negligible. For maximum accuracy at low voltage levels it is best to line up the edge of the spot against a fine hair-line using a low-power microscope.

As a result of transit-time effect, the voltage and frequency ranges are limited and are interdependent. This effect takes place when the phase of the deflecting voltage begins to reverse before the electrons in the beam had sufficient time to cross the deflecting field. The transit time thus reduces the magnitude of the deflection unless it is smaller than a half-period of the highest frequency to be used. The error caused by this effect is usually expressed as a ratio, C, of dynamic to static sensitivity, the sensitivity being the linear deflection per volt. This ratio is expressed as [6,7,8]

$$C = \frac{\sqrt{2(1-\cos\phi) + \phi^2 - 2\phi\sin\phi + 2\phi^2\frac{L}{\ell}\left[1 + \frac{L}{\ell}(1-\cos\phi)\right]}}{\phi^2(1/2 + \frac{L}{\ell})} \tag{7}$$

where

$$\phi = \frac{\omega\ell}{v_o} \tag{8}$$

$\omega = 2\pi f$

$v_o = 5.97 \times 10^7 \sqrt{V_a}$ = beam velocity (9)

V_a = d-c voltage accelerating the beam within the deflection field for $V_a \leq 10{,}000$ v. For higher values of V_a Einstein's correction for the increase in mass of the electron must be applied.

This formula takes into account the beam displacement parallel to the axis. This displacement is usually negligible for large ratios of the L/ℓ, where L is the effective distance between the screen and the deflection field as shown in Fig. 2. In the latter case

$$C = \frac{\sin\phi/2}{\phi/2} \tag{10}$$

Fig. 3 shows C as a function of $\phi/2$, given by equation (10)[9,10].

Another source of error is the effect on the deflection field of the lead inductance and deflection plate capacity. The voltage between the plates is larger than the voltage applied to the outside terminals of the cathode-ray tube (where the voltmeter under calibration is connected), as given by the following expression:[5]

$$E^1 = E \frac{1}{1 - (\frac{f}{f_r})^2} \tag{11}$$

where

E^1 = deflecting voltage
E = applied voltage
f = operating frequency
f_r = plate and lead series resonance frequency.

With present-day commercial-type cathode-ray tubes one can apply this method without frequency correction to approximately 75 Mc over a voltage range of about 5 volts to several hundred volts. The maximum voltage allowable between the plates is determined by properties of other electrodes and general insulation proporties.

The accelerating voltage may be reduced in order to permit accurate measurements below 5 volts. This, however, reduces the frequency range, and, conversely, one can increase the frequency range at the expense of voltage range within the rated limits of the accelerating voltage.

Special applications of this method to frequencies up to 300 Mc and higher are briefly outlined below. The accuracies obtained are not known.

One modification is the replacement of the deflecting plates by a section of a two-wire transmission line, in a plane normal to the axis of the tube, extending beyond the tube in both directions[11]. The beam passing through the spacing between the conductors is deflected in proportion to the voltage at this point of the line. The voltmeter under calibration is placed a distance $\lambda/2$ away along the line where the voltage across the line is the same as at the cathode ray. This method is shown in Fig. 4. The deflection angle θ is given by

$$\theta = \frac{E_{max}}{2\ V_a} \frac{\pi}{\cosh^{-1}(d/2r)} \tag{12a}$$

For large values of d/r

$$\theta \cong \frac{E}{2\ V_a} \frac{\pi}{\ln\ (d/r)} \tag{12b}$$

where d and r are the separation and wire radius, respectively.

The electrostatic field is concentrated within a space between the wires approximately equal in width to the wire separation; the distance responsible for a transit time error is therefore approximately equal to the wire separation.

A line having a 3-mm wire diameter and a 6-mm center-to-center separation results in a sensitivity of 0.3 mm per volt for V_a = 1000 v at a screen distance of 25 cm; this may be compared with a sensitivity of approximately 0.63 mm under the same conditions with deflecting plates having a transit time distance nearly 5 times as large.

Another modification consists of a specially constructed cathode-ray tube employing a short focus lens and very small deflecting plates[6,9]. Fig. 5 shows a diagram of this device referred to as a "microwave" oscillograph. The initial cross section of the beam is reduced to a spot size of 10^{-2} to 10^{-3} mm. The beam passes through the deflecting plates and into the short focus lens. With an optical magnification of about x 50 and V_a = 10,000 v the deflection sensitivity is approximately 0.5 mm per volt; the plate length and separation are about 0.2 inch and the transit time effect is negligible at 1500 Mc. These two modified applications of the cathode-ray tube seem to indicate that this method can be used for precision wide-range voltage measurements to at least 300 Mc simply by reducing mechanical dimensions of cathode-ray tube elements.

(d) Electrostatic voltmeter.

Electrometers and electrostatic voltmeters make use of the force existing between charged conductors. These instruments are essentially condensers with the rotor either fibre-suspended or jewel-pivoted. Commercial instruments have a deflection proportional to RMS values of applied voltages, have a high input resistance and low power consumption at frequencies up to approximately 5 Mc[12].

The major disadvantages of this type of voltmeter are low sensitivity and high input capacity (a few to a few hundred uuf) with the capacity nearly always a function of the instrument deflection. Thus certain difficulties and limitations are introduced when the instrument is connected across a tuned circuit.

The voltage range of present-day commercial electrostatic voltmeters is approximately 20 to 10,000 volts.

2. <u>Accurate moderate precision methods</u>

(a) Vacuum-tube voltmeters

The first vacuum-tube voltmeter was patented by R. A. Heising in 1917[36]. For a number of years prior to that date and up to the present time, these voltmeters have been universally used to measure r-f voltages of the order of a millivolt to several kilovolts. Individual meters cover limited ranges depending on frequency, voltage dividers, amplifiers, and types of tubes employed. The vacuum-tube voltmeter is not used as a high-precision standard voltmeter because it is difficult to determine precisely the law of its voltage-current characteristic as well as to maintain its operation sufficiently constant over a reasonable length of time. In addition, in the case of the most commonly used voltmeters with diode-type tubes, the analytically derived output

contains factors depending upon the nature of the impedance across which the voltage is being measured. Finally the input impedance of the voltmeter is a function of the voltage applied to it[13].

Tubes with more than three electrodes are seldom used for voltages above 0.5 v. Pentodes connected as triodes are desirable for some voltage and frequency ranges as a result of spacing and shielding of the electrodes. Triodes connected as diodes are used for higher voltages.

Vacuum-tube voltmeters are usually calibrated at all frequencies using one of the above standard methods. They may also be calibrated in terms of power or audio-frequency standard instruments, in which case freedom from frequency correction is assumed. For higher accuracy, calibration at the operating frequency is preferred. The major performance desiderata of a vacuum-tube voltmeter for frequencies up to a few hundred megacycles are:

(1) Low-input capacity
(2) High-input resistance
(3) Short-input terminals
(4) High series-resonance frequency of input-lead inductance and capacity
(5) Freedom from transit-time correction
(6) Calibration must not be affected by ordinary line-voltage variations, aging and atmospheric changes, and must have negligible zero-setting drift. Output must be free from noise and fluctuations.
(7) Calibration must hold over a reasonable length of time and shall not be affected by tube replacement.
(8) Maximum voltage range with minimum auxiliary equipment like amplifiers and voltage dividers.
(9) Peak voltage calibration for nonsinusoidal waves; rms for sinusoidal waves.
(10) Linear scale or large number of overlapping scales for square-law indications.

Some relative merits of triodes vs diodes for voltmeter applications are listed below.

Triodes are preferred at frequencies below approximately 20 Mc.

(1) For high sensitivity to small applied voltages,
(2) For lower loading effect on circuit being measured,
(3) For greater reliability of calibration at a power frequency.

Their major disadvantages are:

(1) Voltage levels are usually limited to values low enough to keep the grid from going positive,
(2) The d-c plate current has to be stably balanced out to obtain maximum sensitivity,
(3) Accurate zero setting is rather difficult to maintain as a result of supply voltage variations, aging and warm-up period required,

(4) Triodes may have shorter life and may require more frequent calibrations as compared with diodes,
(5) The input resistance at frequencies of about 100 Mc is lower than that of a diode by a factor of ten[5],
(6) It is difficult to construct a triode having the small interelectrode spacing required to keep transit time and resonance errors to a minimum[5,15,23].

A special diode construction was reported where an indirectly heated cathode in the form of a rod is used and a similarly heated rod is employed as an anode. The two are placed end to end and the heating of the anode rod causes a variation of interelectrode spacing. Thus the spacing can be adjusted to the very minimum before actual contact[54].

The table of Fig. 18 lists fundamental detecting circuit elements of vacuum-tube voltmeters and their major functional characteristics. Associated circuits like regular and feedback amplifiers, current balancing circuits, voltage dividers, voltage stabilizing elements, etc., are equally important in determining sensitivity, linearity, stability, and range of the meter[14,16,17,18,19]. Voltage dividers specially constructed to fit given mechanical and electrical requirements may be used to measure high voltages at high frequencies. One arrangement is shown in Fig. 6 for measurements of voltages up to 10,000 volts with frequencies up to 50 Mc[20].

(b) Nonthermionic rectifiers

In addition to thermionic diodes, other rectifiers are used as r-f voltmeter diode elements. These may be broadly subdivided into two classes, - copper-oxide or selenium rectifiers and crystal diodes.

Copper-oxide and selenium rectifiers: These types of rectifier have good overload characteristics and ruggedness. They are, however, affected by temperature and aging, have a relatively large shunt capacitance and a high voltage drop. The approximate equivalent circuit is given in Fig. 7[21,22]. The capacitance is approximately 0.02 uf per square centimeter of contact surface. $R_1 \approx 2$ ohms for one square cm and R_2 with polarity connections for maximum resistance (i.e., backward resistance) is approximately 11,000 ohms for one square cm at applied voltages of -0.25 to -3 volts; this holds over a frequency range of 50 kc to 5 Mc. The forward resistance is several ohms/cm^2 at 25°C and decreases slightly with increasing temperature. Backward resistance is considerably affected by temperature changes. Fig. 8 shows direct-current characteristics of some of these rectifiers[22]. The rectified current depends on temperature, load resistance, frequency, and current density. This type of rectifier is manufactured in all sizes down to pinhead dimensions for currents of a few milliamperes.

Copper-oxide rectifiers are preferred to selenium types for instrument application because of their lower resistance. Selenium types may be operated up to about 10 volts per disc as against about 2 volts for copper-oxide.

Commercial-type copper-oxide voltmeters are available for frequencies to approximately 30 kc and can be designed up to 1 Mc[22]. The major frequency-limiting element is the shunt capacitance C. The effect of the wave form of the applied voltage is appreciable; the error in the indicated output calibrated in terms of sinusoidal input may approach in magnitude the percentage of harmonic content of the voltage measured. These rectifiers are used in series with resistors forming 1000 ohm per volt instruments. They are very much higher in sensitivity and draw considerably less current from the source than the iron-vane or thermocouple-type instruments. However, because of inferior accuracy they are not recommended when the power of the voltage source measured is of the order of a watt or more[22].

Crystal diodes: Whereas copper-oxide rectifiers are applicable as voltage indicators only at the lowest frequencies considered here, modern crystal rectifiers are useful up to 300 Mc and higher.

Crystals most commonly used at present are silicon and germanium.

Table I shows the chemical composition of some of these crystals[26]. Other crystals are galena, iron-pyrites, carborundum and other materials known as semi-conductors. The major difference between crystal diodes and copper-oxide rectifiers is that the contact area and consequently power handling capacity of the crystals are much smaller.

Fig. 9 shows the mechanical construction of a modern-type crystal diode; Fig. 10 shows a typical static characteristic of a germanium crystal, and Fig. 11 shows its rectification efficiency characteristic for different loads and frequencies; Fig. 12 shows the rectification efficiency of an iron-pyrites rectifier[24,25,26,27].

Fig. 13 shows the equivalent circuit of a crystal unit where R_e and C_b are the non-linear resistance and shunt capacity of the barrier layer and R_s is the resistance of the body of the semi-conductor[27,28].

Relative merits of crystal vs thermionic diodes for r-f voltage measurements are listed as follows.

Advantages of crystal diodes:

(1) Transit-time effect is negligible. As a result of transit-time effect, the rectification efficiency in acorn-type thermionic diodes begins to drop off at 30 Mc for voltage levels of 0.5 v. This reduction is 30 percent at 500 Mc.

(2) The crystal has smaller physical dimensions, and therefore a higher input resonant frequency. This is approximately 3500 Mc as against 1500 Mc for the smallest commercial thermionic diode.

(3) No constant cathode temperature is required, as in the case of a vacuum tube, to maintain constant emission.

(4) Crystals can be used at lower voltage levels than vacuum diodes.

Relative disadvantages of crystals:

(1) They have poorer stability, ruggedness and uniformity between individual units.

(2) They are frequency-sensitive partly for the following reasons: the capacity C_b (Fig. 13) shunts the "reverse" resistance of the barrier (C_b is 0.2 to 0.6 uuf for good commercial units); this causes a drop in rectification efficiency. The barrier layer resistance and capacity are functions of the voltage level applied across this barrier[25,28]; the magnitude of this voltage is in turn a function of C_b, R_e and R_s acting as a voltage divider; R_s varies between 5 to 100 ohms for different types of crystals. This effect is however negligible for some units at frequencies below 500 Mc in circuits having relatively high crystal load resistance. Figs. 11 and 12 show typical frequency characteristics of two commercial types of crystals.

(3) Reverse rectification at the contact between the crystal and its supporting electrode and the relatively large shunting capacity at this contact introduces another error. In the particular case of an iron-pyrites crystal this error amounts to a 50-percent increase in the output at 10 Mc as compared with the output at 1 Mc[27]. Plating or fusing the crystal in place largely eliminates this effect.

(4) The input impedance of crystal and probe is comparable with that of a thermionic diode and its probe at ultra-high frequencies. At lower frequencies the V-T diode has a higher input resistance than the crystal.

(5) The voltage range of commercial crystal units available at present designed for high back voltage and for frequencies up to 100 Mc is limited to a maximum of approximately 30 v rms. Those recommended for higher frequencies have a maximum rating of approximately 1 v rms[25,26]. Overloading causes a change in characteristics or permanent damage to the contacts.

(6) Resistance and sensitivity vary with temperature as shown in Fig. 14[25].

A crystal-type voltage indicator was recently placed on the market[28]. It has a range of 0.1 to 1 volt with a $\pm$ 5% claimed accuracy from 10 to 300 Mc. The "forward" resistance of the crystal is of the order of a few hundred ohms; in the "reverse" direction it is 15,000 to 100,000 ohms. The crystal is used in a peak reading circuit. The input resistance of the meter is approximately one-third of the "reverse" resistance. An improved construction of a germanium crystal was announced having an optically polished face of specially processed germanium and a platinum "whisker" point welded to that plane; stability and constancy of performance superior to that employing pressure-type contact is claimed[29].

3. Pulse-peak voltage measurement

(a) Cathode-ray deflection

The most accurate method of measuring peaks of voltage-pulses employs

a cathode-ray oscilloscope. When properly synchronized the shape of the pulse can be observed and the peak measured at any desired point of the pulse. Deflections can be measured directly on the screen or a d-c voltage slide-back circuit arrangement similar to the one shown in Fig. 2 may be used. Resistance or capacitance dividers are frequently used for high peak measurements. Precautions must then be observed so as not to affect appreciably the shape of the pulse.

(b) Diode peak voltmeters

Diode peak voltmeters are generally used as convenient moderate-precision indicators[30,31]. However, the discrepancy between the voltmeter reading and true peak value may be very large. Fig. 15[30] shows the response of a commercial diode-type vacuum-tube voltmeter as a function of pulse repetition frequency. The pulse duration is 5 microseconds and the "duty cycle", defined as the ratio of pulse width to its repetition period, can be computed. An approximate expression is derived in the reference given for the pulse peak in terms of the d-c diode output

$$\mathcal{E}_0 \simeq E_{dc}\left[1 + \left(\frac{T}{t_1}\right)\left(\frac{R_1}{R_2}\right)\right] \tag{13}$$

where

$\mathcal{E}_0$ is the peak voltage of a rectangular pulse
E_{dc} is the d-c voltage across R_2
T is the duration of the pulse
t_1 is the duration of the charging interval
R_1 is the total resistance during charging
R_2 is the total resistance during discharging

One of the curves of Fig. 15 shows values computed on the basis of this expression. For this type of voltmeter the effective input impedance to pulse voltage may be very low, and it increases with increasing pulse repetition, with increasing values of R_2 and with decreasing values of R_1. R_1 is a function of the combined source and diode resistances at the particular operating conditions. Improved performance may be obtained by means of auxiliary circuits like cathode followers[30] and automatic slideback arrangements[31].

4. Miscellaneous methods

The following voltage measuring methods are of interest as relatively independent and useful for certain applications.

(a) Heterodyne method of extending the voltage range[32].

This principle is illustrated in Fig. 16. A diode frequency changer, D, mixes voltages E_0, supplied from an auxiliary source, with E_x^1 a fraction of the unknown voltage E_x used to calibrate V_x. The magnitude of E_x^1 is determined by the value of C. The intermediate-frequency output voltage is directly proportional to E_x for large ratios of E_0/E_x^1. One can thus use a single calibration point of V_x determined at a low voltage (e.g., 1 volt obtained by means of the bolometer or any of the other

standard methods listed above) and proceed with calibrating a voltmeter V_x at high voltages. The advantage of this method is that it can be used to calibrate high voltage levels at high frequencies in terms of a standard attenuator used at a relatively low intermediate frequency. The use of a crystal diode may eliminate the transit time error at frequencies up to several hundred megacycles.

(b) Spark-gap method.

Spark gaps may be used to measure peak voltages of the order of 1 to 30 kv at all frequencies up to about 100 kc[33]. The sphere spark gap is preferred to other electrodes because the breakdown voltage changes little up to about 25 kc. For a symmetrical sphere-gap voltmeter the peak voltage is given approximately by

$$E = \sqrt{2}\,\mathcal{E}\,\frac{\ell}{m}\text{, where} \tag{14}$$

$$\mathcal{E} = 19.3\,\rho\left[1 + \frac{0.76}{\sqrt{pD}}\right] \quad \text{KV/cm}$$

$$\rho = \frac{3.92p}{T} = \text{relative air density}$$

D = sphere diameter in cm

ℓ = distance in cm just before sparking takes place

p = atmospheric pressure in centimeters of a mercury column

T = (273 + N° C) = absolute temperature in °K

and

$$m = 0.25\left[\frac{2\ell}{D} + 1 + \sqrt{\left(\frac{2\ell}{D} + 1\right)^2 + 8}\right]$$

(c) Glow-discharge voltmeter

A method applicable for peak voltages up to about 15 kv and frequencies up to 1 Mc makes use of a glow tube as shown in Fig. 17[33]. The value of C is continuously decreased until the peak value of the voltage across it is just equal to a predetermined critical value E_c that is causing the tube to glow. The value of E_x may then be computed from known values of C, C_1, and C_2 where C_2 is the tube and distributed input lead capacity.

(d) Electrometer employing miniature open-wire line

An electrometer consisting of a short platinum open parallel wire line is reported applicable for measurement accuracies of 1.5% over a frequency range of 30 to 100 Mc and voltage range of 10 to 70 v[42]. The wire diameter is 0.01 mm, line separation 1 mm, and line length approximately 5 cm. One of the lines is tightly mounted while the other is kept under relatively low tension. The deflection of the latter is observed under a microscope and calibrated at 100 kc and at dc, the two calibrations yielding identical results. Varying the

tension of the wire under observation provides a control of the voltage range which could be increased to 300 volts. A major advantage of this method is claimed to be the high input impedance, the capacity of the electrometer being less than 0.5 uuf. The maximum reduction in line separation (with a consequent effect on the characteristic impedance and voltage distribution) is 10 percent; this contributes an error of less than 0.1% to the voltage measurements at all frequencies up to 100 Mc.

(e) Electrometer employing suspended wire

An electrostatic voltmeter employing a suspended wire described by Peterson[55] may be used at high voltages and frequencies up to 1000 Mc or higher. It consists of a 3.5-cm long, 0.0013-cm diameter platinum wire suspended inside a 2.5 by 1.1-cm opening of a brass block. The wire is spaced 0.16 from the 1.1-cm side and the deflection of its free end is measured after the r-f voltage is applied between the insulated suspension terminal and the brass block. A deflection of about 2 cm may be obtained for 10 volts when the shadow of the wire is projected optically on a screen with an effective deflection magnification of 1000. The deflection is increased ~~reduced~~ by about 3% at 300 Mc and 33% at 1000 Mc as compared with that of dc.

The listed difficulties encountered with this voltmeter are as follows:

(1) A darkened room may be required.
(2) The meter is very sensitive to motions of the building and should preferably be used in the dead of night.
(3) The heat from the projector lamp causes a drift of the wire position.
(4) It cannot be used at low frequencies where the low inertia of the wire is insufficient to prevent wire vibration.
(5) The input capacity is a function of the voltage applied, which may sometimes be objectionable.

A considerable amount of valuable analytical and experimental information on the application of the bolometer, thermoelement and diode rectifier for r-f voltage measurements is given by Peterson in addition to the electrostatic voltmeter described above.

Nomenclature of Table of Fig. 18

I_{po} - d-c plate current without applied r-f voltage

I_p - d-c plate current

I_g - d-c grid current

V - d-c voltage

ΔV - d-c voltage increment

ΔI_p - increment of d-c plate current

ΔI_g - increment of d-c grid current

μ - amplification factor

g_m - mutual conductance

r_p - plate resistance

R_l - load resistance

R_g - resistive component of grid input impedance

V_g - d-c grid bias

μ_o, g_{m_o}, r_{p_o}, $\left(\frac{\partial g_m}{\partial e_g}\right)_o$, are values determined at a given quiescent point corresponding to E_{go} and I_{po}.

E_1, E_2, E_3 - amplitudes of harmonic components of a complex periodic wave.

i_p - instantaneous plate current

e_g - instantaneous grid voltage

e - instantaneous voltage

E_{max} - maximum value of r-f voltage

E - rms value

E_g - rms grid voltage

E_{ave} - average voltage over half-cycle of a periodic wave

$$E_{ave} = 0.637E_{max} = 0.901E$$

f - frequency in cycles per second

f_r - resonance frequency

K - a constant

d_a - distance between anode and cathode of a vacuum tube

η - rectification efficiency

λ - wavelength

τ - electron transit time.

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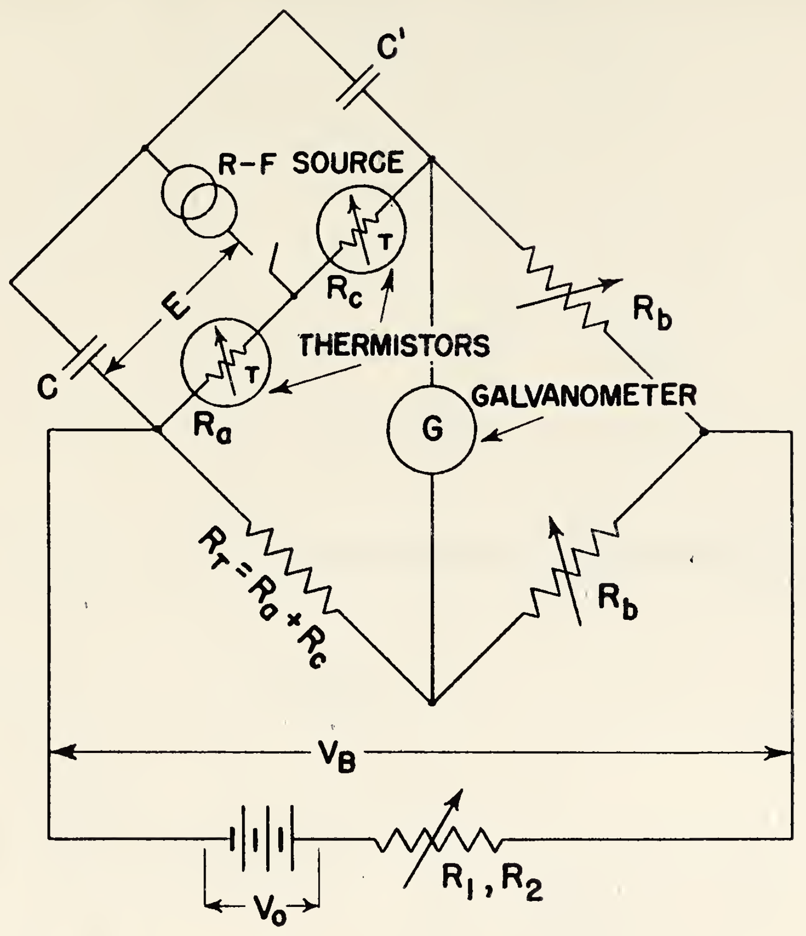


Fig. I. GENERAL BOLOMETER BRIDGE CIRCUIT EMPLOYING TWO THERMISTORS

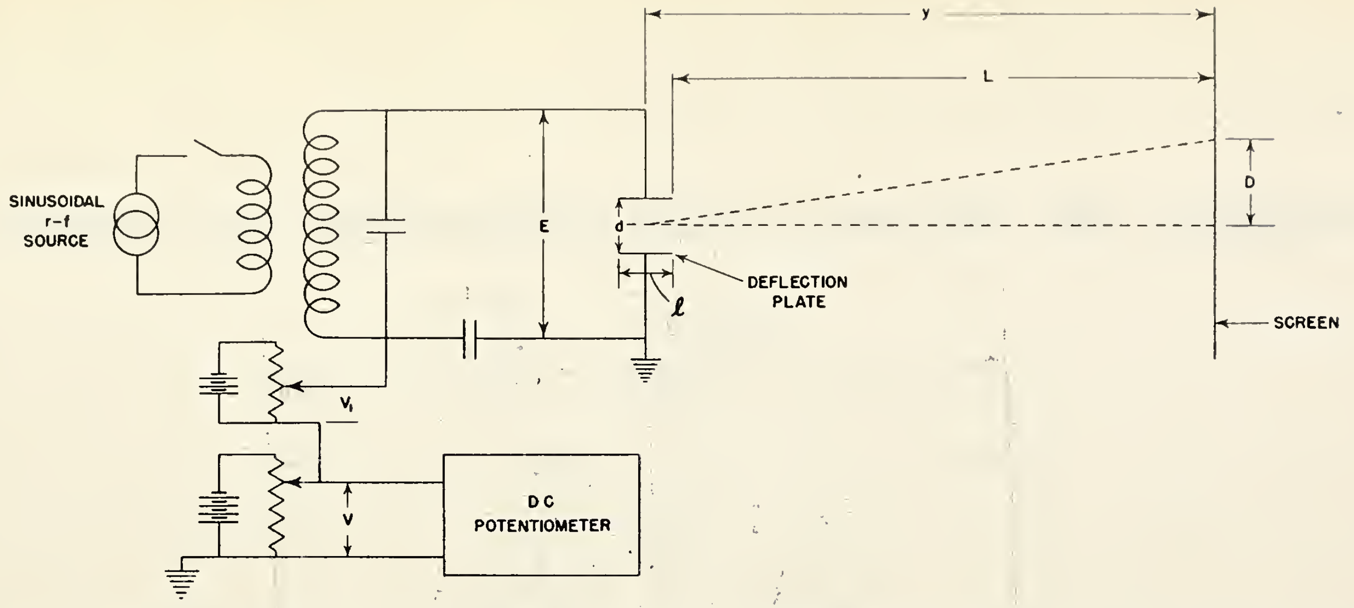


Fig. 2. ESSENTIAL COMPONENTS OF R-F VOLTAGE MEASURING CIRCUIT ARRANGEMENT EMPLOYING DEFLECTION OF CATHODE-RAY BEAM

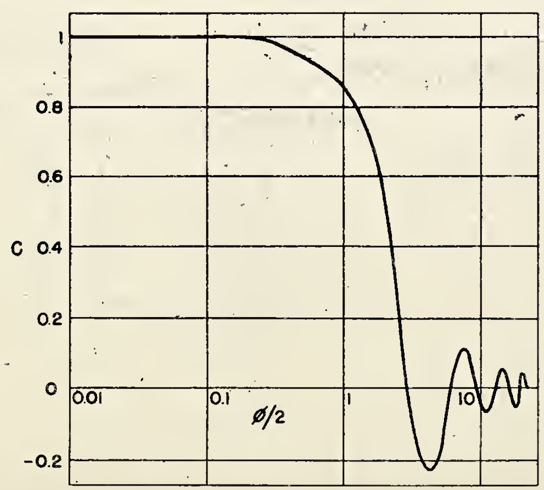


Fig. 3. EFFECT OF ELECTRON TRANSIT TIME ON SENSITIVITY OF CATHODE-RAY TUBE

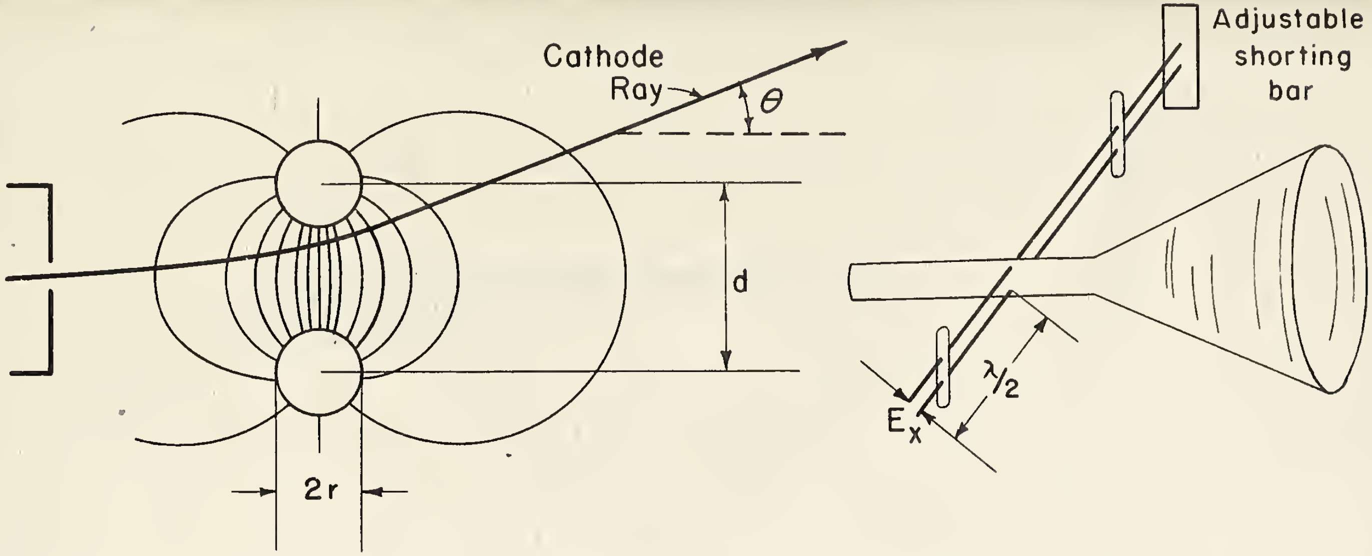


Fig. 4. TUNED TRANSMISSION LINE DEFLECTION SYSTEM.

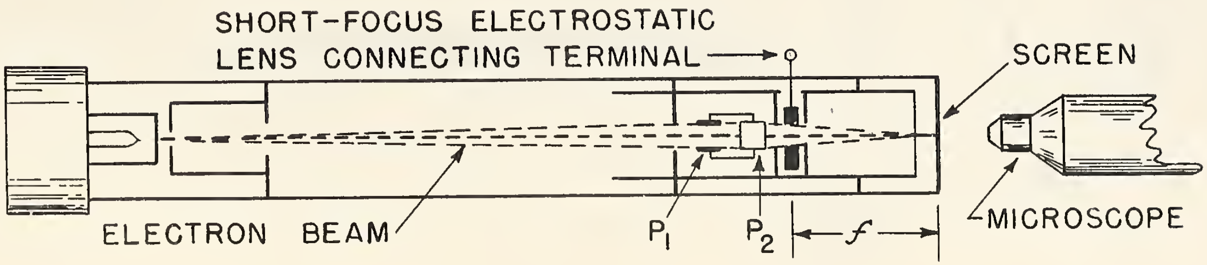


Fig. 5 DIAGRAM OF MICROWAVE OSCILLOGRAPH

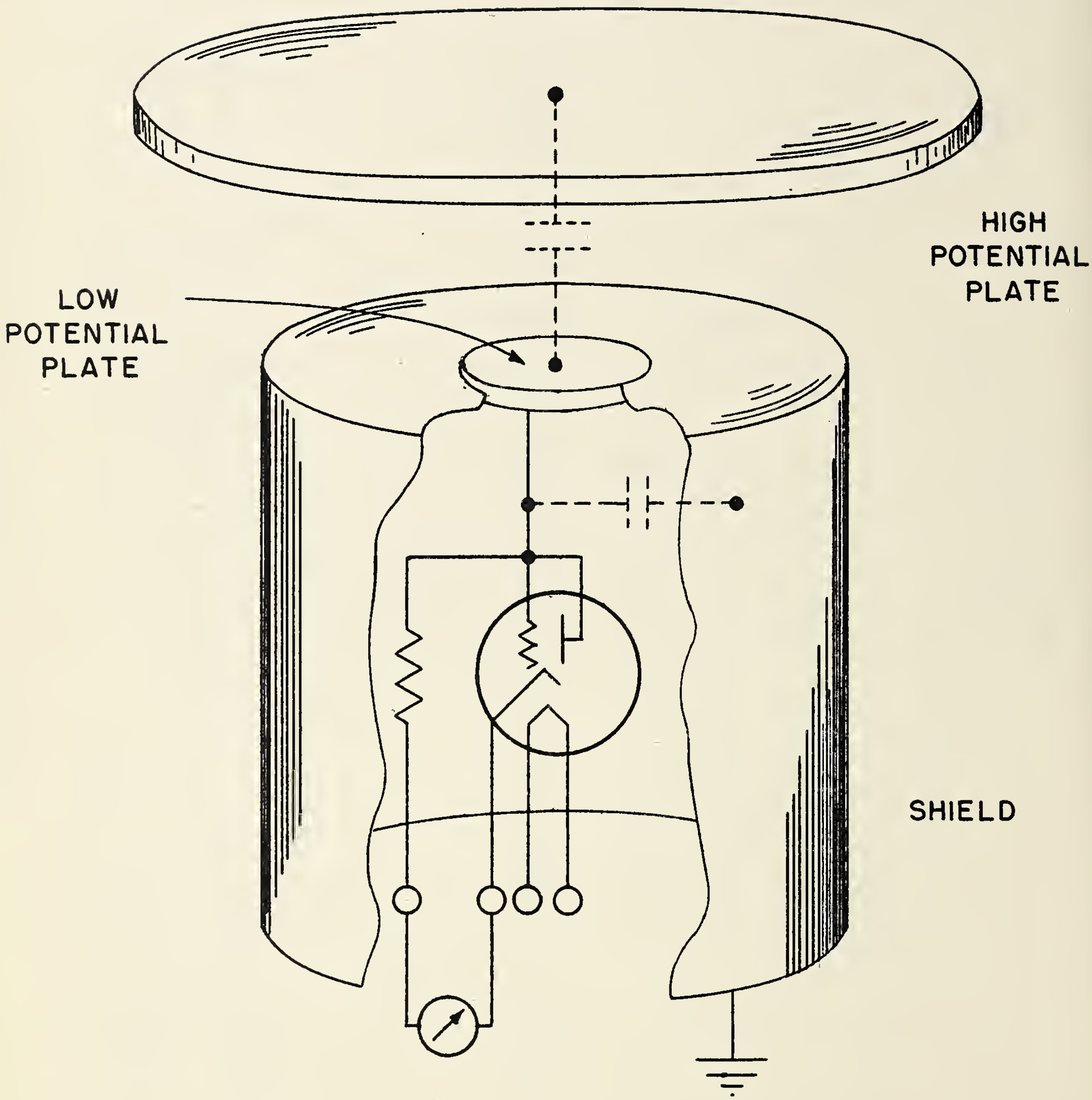


Fig. 6. VTVM AND VOLTAGE DIVIDER FOR VOLTAGES UP TO 10,000 VOLTS.

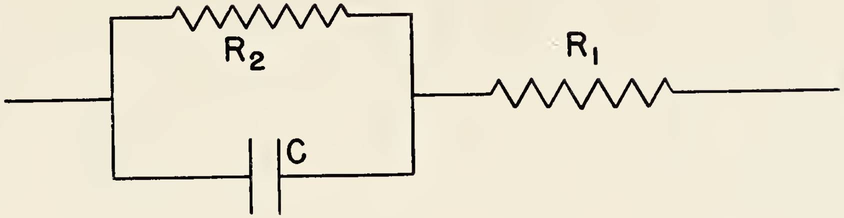


Fig. 7 APPROXIMATE EQUIVALENT CIRCUIT OF COPPER OXIDE RECTIFIER IN THE 50 kc TO 5 Mc RANGE. R_1 IS THE RESISTANCE OF THE BODY OF THE OXIDE. R_2 IS THE RESISTANCE OF THE OXIDE-COPPER INTERFACE AND IS DEPENENT ON POTENTIAL.

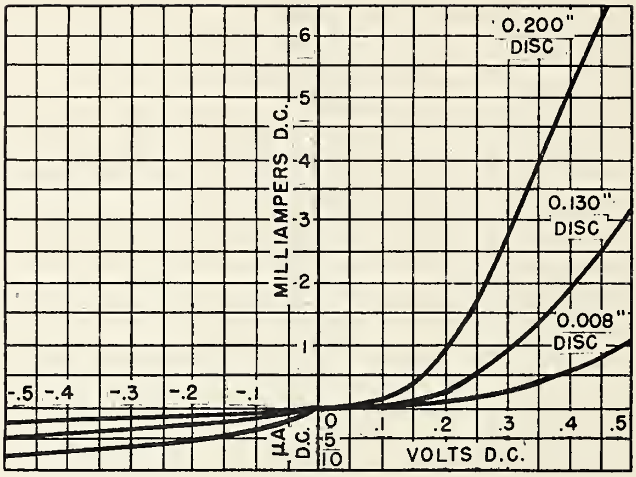


Fig.8 DIRECT CURRENT CHARACTERISTICS OF COPPER OXIDE RECTIFIERS

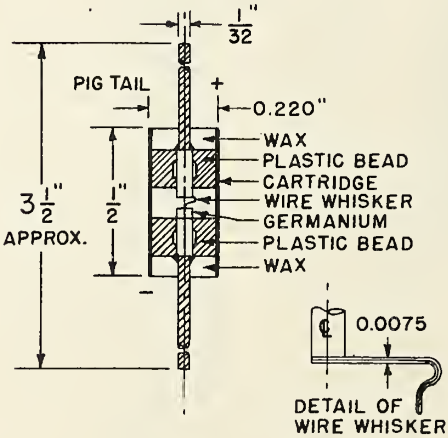


Fig. 9 CONSTRUCTIONAL DETAILS OF TYPE IN34 GERMANIUM CRYSTAL DIODE

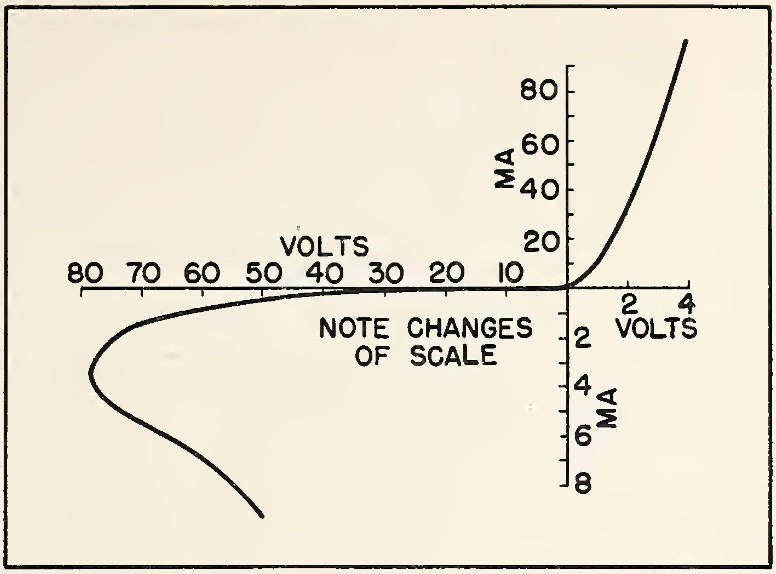


Fig. 10. D-C CHARACTERISTIC OF GERMANIUM DIODE

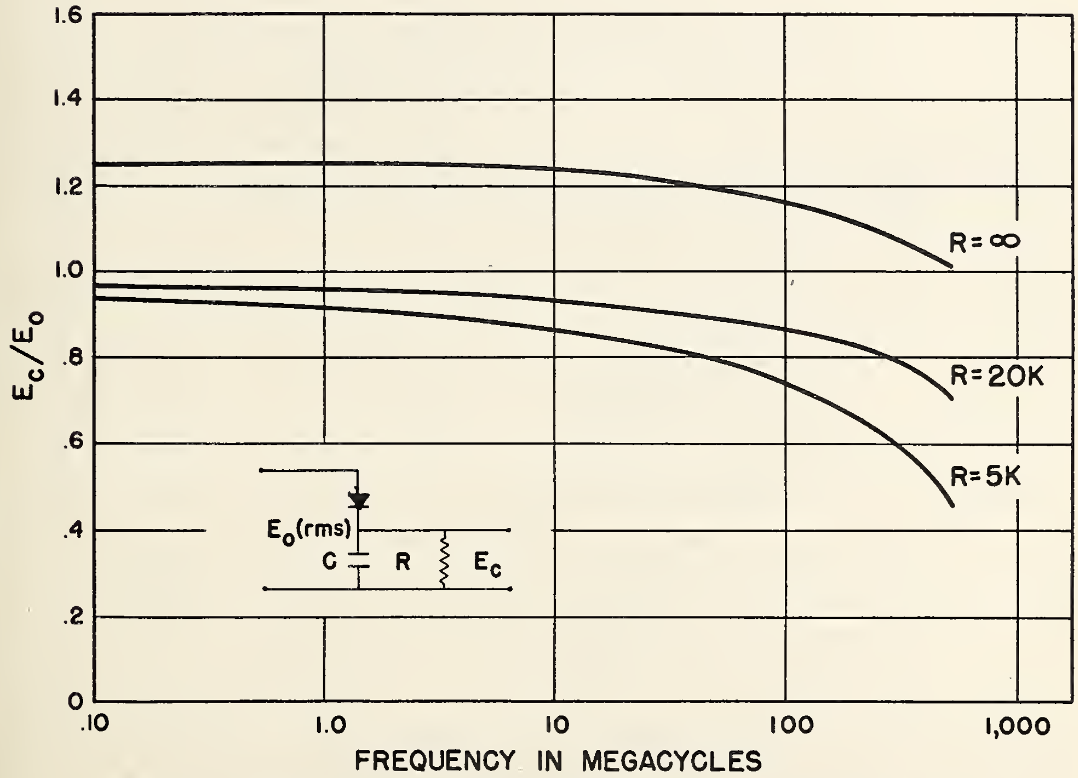


Fig. 11. RECTIFICATION EFFICIENCY CHARACTERISTICS
OF A GERMANIUM CRYSTAL

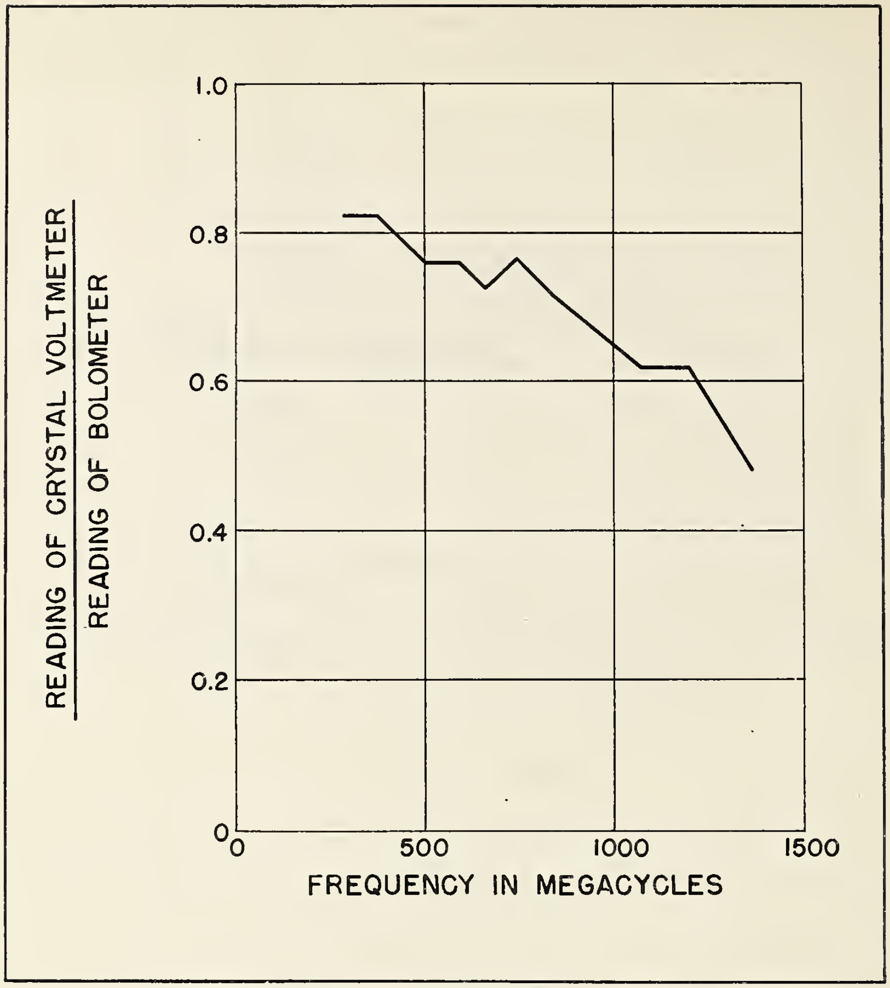


Fig. 12. RECTIFICATION EFFICIENCY OF AN IRON-PYRITES RECTIFIER.

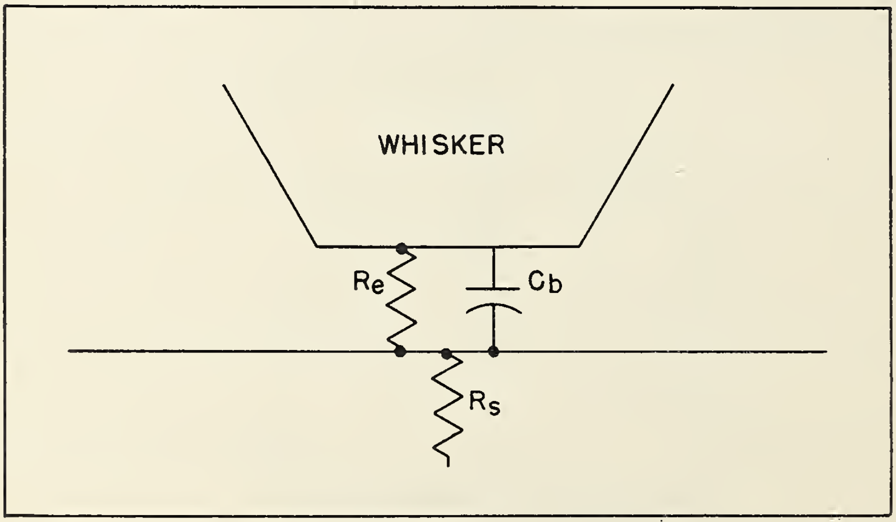


Fig. 13. EQUIVALENT CIRCUIT OF A CRYSTAL RECTIFIER.

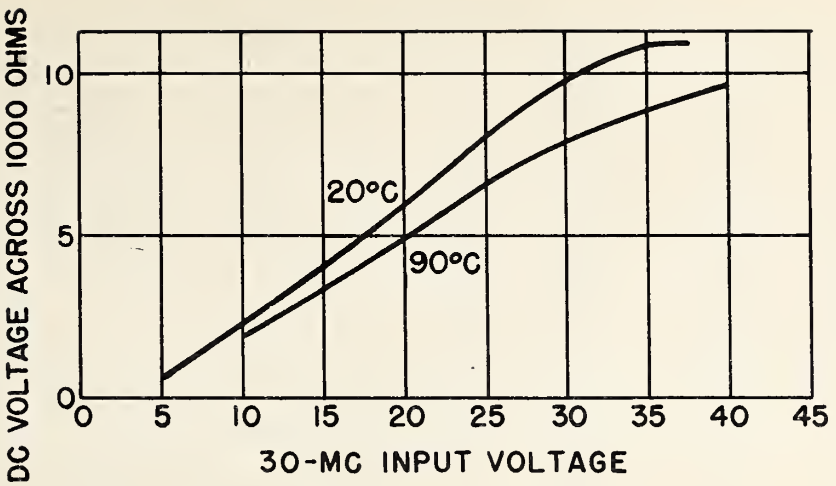


Fig. 14. RECTIFIED DC FROM A HIGH-BACK-VOLTAGE SILICON CRYSTAL AS A FUNCTION OF TEMPERATURE.

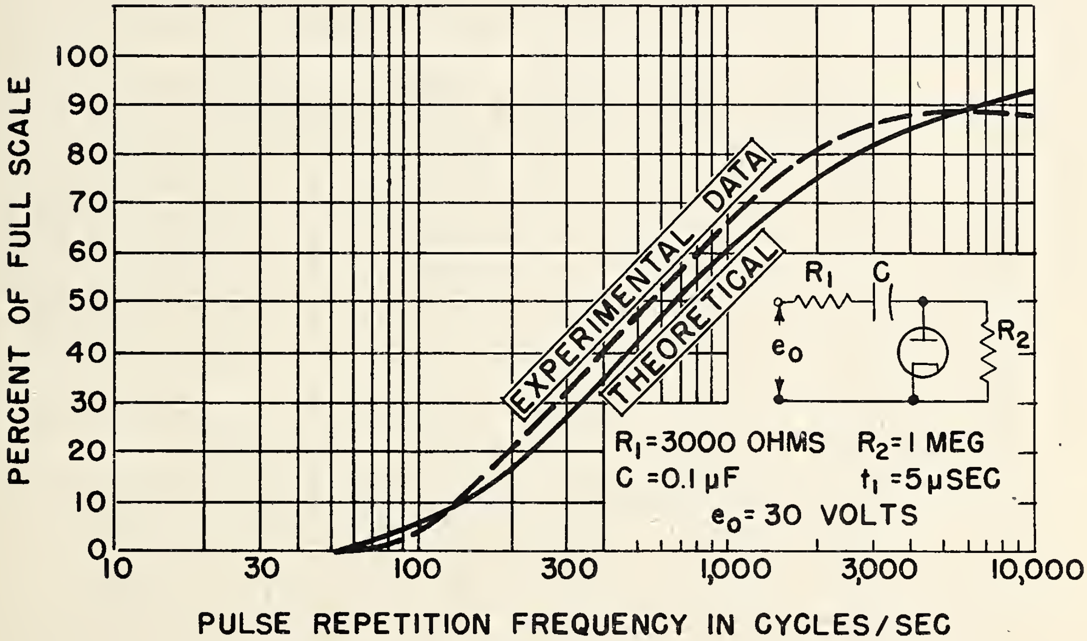


Fig. 15. RESPONSE OF A COMMERCIAL DIODE-TYPE VTVM AS A FUNCTION OF PULSE REPITITION FREQUENCY.

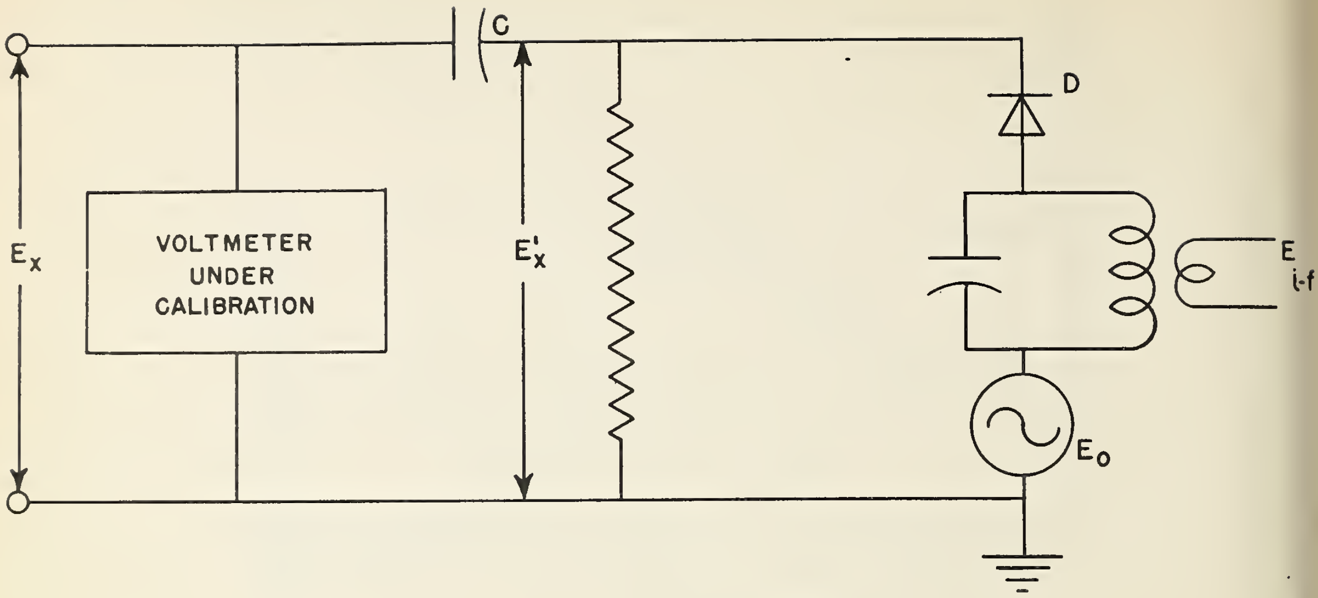


Fig. 16. HETERODYNE PRINCIPLE OF CALIBRATING R-F VOLTMETERS.

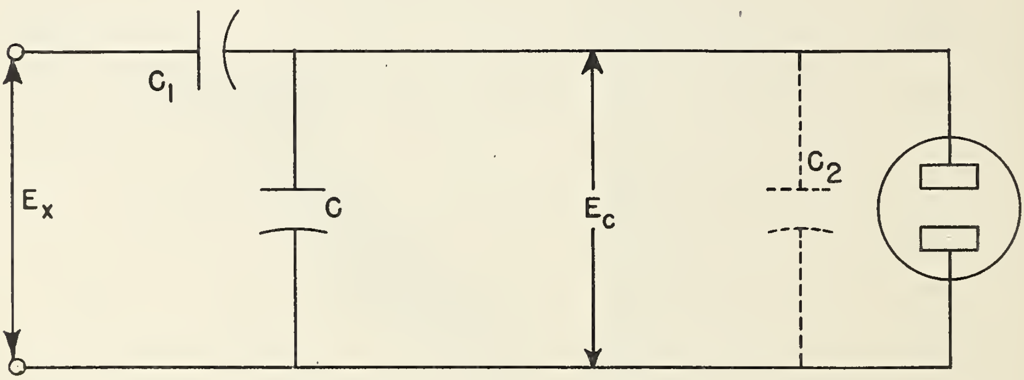


Fig. 17. GLOW-DISCHARGE TUBE VOLTMETER.

ELEMENTARY CIRCUITS AND CHARACTERISTICS OF VACUUM-TUBE VOLTMETERS

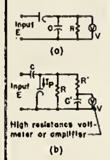
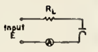
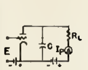
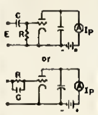
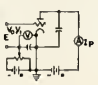
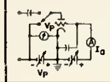
TYPE	CIRCUITS	PRINCIPLE OF OPERATION	BASIC FORMULAE	APPROXIMATE INPUT IMPEDANCE	OUTPUT OF COMPLEX WAVEFORM	EFFECT OF WAVEFORM	APPROXIMATE VOLTAGE RANGE	FREQUENCY RANGE AND ERROR	CALIBRATION STABILITY	REMARKS
1. Diode Detection		In circuits (a) and (b) C charges to E peak. R acts to discharge C. 13, 15, 16, 17, 48, 49, In circuit (b), R' and C' act as a filter to keep r-f out of the d-c measuring circuit. NOTE: Numbers refer to list of references.	For linear diode characteristics $V_{dc} = KE$ peak. Equivalent input resistance = $\frac{R}{2\frac{I_p R}{E_{peak}}} = \frac{R}{2\eta}$ η approximately unity as R and E increase. For square-law type diode η is a function of E. 13, 15. NOTE: See list of nomenclature on page 18.	In general it is a function of R and amplitude of E. There is a value of R at which the input impedance is practically independent of E. The order of magnitude is the equivalent of 1 to 25 megohms resistance shunted with an input capacity of 3-10 μμf. 10^6 ohms at 300 Mc. is possible. 13	E_{peak}	The source impedance must be negligible at all harmonics, and the level of harmonics must be low otherwise error may be as large as the percentage harmonics present. 13	The upper limit depends on tube rating. With sensitive d-c voltmeter or with d-c amplifier the lower limit is a fraction of a volt. Range depends on frequency; the higher the frequency, the narrower the range; correction may be applied.	Upper limit as affected by: (1) Series resonance of input L and C anode to cathode r-f voltage = $E\frac{1}{1-\left(\frac{f}{f_r}\right)^2}$ 2% for a type 955 vacuum tube at 100 Mc. (2) Transit time error = $\frac{\Delta V}{V} = \frac{Kda}{\lambda\sqrt{E\,peak}}$ 3% at 100 Mc with 955 "acorn" at 10v Range is therefore a function of voltage applied. Correction curves may be used to extend the range. Overall ± 12% is obtainable without correction for E > 0.5v. 16, 5.	Good. Depends on the constancy of filament voltage and emission. May require yearly calibrations.	This circuit, followed by a self-biased d c amplifier seems to be the prefered type most suitable for the widest frequency range. To eliminate low-frequency discrimination, the product of RC should equal at least 100 at the lowest value of frequency. The effect of series resonance of the input to the tube is to: (1) Increase the apparent input voltage of the fundamental frequency (2) Emphasize harmonics more than the fundamental. For high voltages, triodes connected as diodes or power rectifiers are used.
2. Diode Rectification		$R_p = 0$ by assumption $I_{p_0} = 0$ by assumption $R_L I_{ave}$ = average voltage of the positive half cycle 43, 56, 57, 58, 59.	For a sinusoidal input $I_p = \frac{1}{\pi R_L} E_{max}$	$2R_L$	E_{ave}	Not subject to turnover. 45 (i.e. no error is caused by reversing input terminals even in the case of unsymmetrical wave-form consisting only of fundamental and its harmonics.)	A fraction of a volt to a few hundred volts and higher depending on the value of R_L and tube voltage ratings.	Should be calibrated at the operating frequency when used in the neighborhood of 1 Mc and higher. Probable useful range up to several Mc.	Same	R_L may vary from 0 to 1 megohm. For $R_L \geq 100{,}000\ \Omega$, error caused by slight curvature of static tube characteristic is negligible 51.
3. Plate Detection Full wave, square law.		Approximate parabolic lower curved portion of I_p-E_c characteristic is used. Average plate current is higher than the quiescent plate current. Biased for $i_p > 0$ throughout the cycle. R_L (except of current meter) is usually omitted. 60.	$\Delta I_p \simeq K(E_1^2 + E_2^2 + E_3^2 + \cdots)$ to a first approximation. $\Delta I_p = \frac{1}{4\mu_a g_{m_0}(r_p + R_L)}\left(\frac{\partial g_m}{\partial E_g}\right)(E_1^2 + E_2^2 + E_3^2 + \cdots)$ 40	Approximately 10^7 ohms resistive at frequencies up to a few mc. shunted by $(C_{gp} + C_{gc})$ May drop to 10^4 or 10^3 at 300 Mc. depending on the tube. 5 $R_g = \frac{1}{K g_m f^2 \tau^2}$ 41, 35, 61.	$(E_1^2 + E_2^2 + E_3^2 + \cdots)$	In practice ΔI_p will depend to some degree upon wave form. Theoretically there is no turnover. Phase of harmonic has no effect.	Fraction of a volt to top limit within square law range of tube (a few volts for commercial tubes)	With present commercial type tubes, a low-frequency calibration will hold within 5-10% to 20 or 30 Mc. At higher frequencies calibration at each frequency is necessary. 39	Poor as a result of tube ageing and variations in the d-c voltages.	Noise output can be corrected for by subtracting it from total output, 40 i.e. $\Delta I_x = \Delta I_{Total} - \Delta I_{Noise}$
4. Plate Detection Half wave, square law	Same	Same as above except tube is biased to cutoff. For large R_L and C = 0, i_p is nearly proportional to e_g during positive half cycles.	For relatively large values of R_L and E, $I_p \simeq KE_{ave}$. For small r-f voltages and low values of R_L, $I_p \simeq K(E_1^2 + E_2^2 + E_3^2 + \cdots)$	Same as above	E_{ave} if plate current characteristic is linear. E_{rms} if plate current characteristic is parabolic.	Subject to turnover and phase of harmonics.	Fraction of a volt to a value of E causing grid current flow.	Same	Same	
5. Plate Detection Peak	Same	Tube is biased appreciably beyond cutoff.	$I_p \simeq KE_{Peak}$	At negligible transit time effect $R_g \simeq \frac{K}{f}$ 41, 44. $C_g = (C_{gp} + C_{gc})$	Not recommended. Error might be appreciable.	Subject to turnover and phase of harmonics.	From $E_{max} \simeq V_c$ to values causing flow of grid currents.	Same	Same	
6. Grid-detection		Operation takes place along the lower curved portion of the grid-current grid-voltage characteristic and over the straight or the curved portions of the I_p-E_g characteristic. $X_c \ll R$	$\Delta I_p = g_m R \Delta I_g$ over the linear portion of the I_p-E_g characteristic.	Relatively low	E_{rms} or E_{peak} depending on input level and operating voltage.	Error may be appreciable.	Fraction of a volt to a few volts with receiving type tubes.	Approximately to 10 Mc.	Very poor.	When plate rectification takes place in addition to grid rectification, ΔI_p may equal zero at a certain level of E. 51
7. Slide Back		D.C. bias adjusted to obtain same plate current with r-f as was obtained without r-f (i.e. with input terminals shorted) $I_p - I_{p_0}$ = a few microamperes. 34	The peak of the positive half cycle = $E_{max} = K(V_1 - V_0)$. K approaches unity as E increases and as the sharpness of cutoff increases. It may be as low as 0.2 and lower depending on the tube characteristic and on the magnitude of E. V_0 = d-c voltage at E = 0 V_1 = d-c voltages at other values of E.	$\frac{1}{\omega(C_{gp} + C_{gk})}$ Input resistance is approaching leakage resistance across input terminals. 34, 61	E_{peak} of positive half cycle.	Subject to turnover.	Fraction of a volt to a few hundred volts. Calibration is indispensible especially for voltages below approximately 10 volts calibration should be made for a given I_p.	Approximately to 10 or 20 Mc depending on input capacity	Good. Practically independent of ageing and operating voltage variations	Sharp cut off is obtained with pentodes connected as triodes with screen grid used as the control element. 37
8. Inverted Triode		I_g is reduced when an r-f voltage is applied to the input terminals. V_p is negative. 38	$E_{peak} \simeq V_p$ required to produce the same I_g. Amplification factor $\simeq \frac{1}{\mu}$	Resistance of the order of 1000 megohms shunted by $C_{kp} + C_{pg}$. 38	E_{peak}	Subject to turnover.	Large voltages, depending on tube design.	Possibly to 10 Mc. Theoretically limited by the input capacity. No experimental data available.	Probably good. No experimental data available.	

Fig. 18

Table I Composition of Crystal Rectifiers

Bulk material	Impurities added		
	High-frequency mixer crystals	High-back voltage crystals	Low-frequency rectifiers
Silicon	Aluminum Boron	Germanium also Ni Sn Bi Co	Aluminum Boron Germanium also Mo Ta Zr Co W Re Be Fe
Germanium	Antimony also P Fe	Tin also Co Ni Sr Bi N	Antimony Tin